

Time-Reversal Invariance Violation in Heavy and in Few-body Nuclei

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Abstract. Time reversal invariance violating (TRIV) effects in neutron scattering are very important in a search for new physics, being complementary to neutron and atomic electric dipole moment measurements. In this relation, a sensitivity of TRIV observables to different models of CP-violation and their dependencies on nuclear structure, which can lead to new enhancement factors, are discussed.

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TRIV in nuclear physics has been a subject of experimental and theoretical investigation for several decades. One important advantage to the search for TRIV in nuclei is the possibility of an enhancement of T-violating observables by many orders of magnitude due to the complex nuclear structure (see, i.e. paper [1] and references therein). Moreover, the variety of nuclear systems to measure T-violating parameters provides assurance that a possible “accidental” cancelation of T-violating effects due to unknown structural factors related to the strong interactions in the particular system would be avoided. Taking into account that different models of the CP-violation may contribute differently to a particular T/CP-observable¹, which may have unknown theoretical uncertainties, TRIV nuclear effects could be considered valuable complementary experiments to electric dipole moment (EDM) measurements.

One of the promising approaches to the search of TRIV in nuclear reactions is the measurement of TRIV effects in a transmission of polarized neutrons through a polarized target. For the observation of TRIV and parity violating (PV) effects, one can consider effects related to the $\vec{\sigma}_n \cdot (\vec{p} \times \vec{I})$ correlation, where $\vec{\sigma}_n$ is the neutron spin, \vec{I} is the target spin, and \vec{p} is the neutron momentum, which can be observed in the transmission of polarized neutrons through a target with a polarized nuclei. This correlation leads to a difference [2] between the total neutron cross sections $\Delta\sigma_{TP}$ for $\vec{\sigma}_n$ parallel and anti-parallel to $\vec{p} \times \vec{I}$ and to neutron spin rotation angle [3] ϕ_{TP} around the axis $\vec{p} \times \vec{I}$

$$\Delta\sigma_{TP} = \frac{4\pi}{p} \text{Im}(f_+ - f_-), \quad \frac{d\phi_{TP}}{dz} = -\frac{2\pi N}{p} \text{Re}(f_+ - f_-). \quad (1)$$

Here, $f_{+,-}$ are the zero-angle scattering amplitudes for neutrons polarized parallel and anti-parallel to the $\vec{p} \times \vec{I}$ axis, respectively; z is the target length and N is the number of target nuclei per unit volume. The unique feature of these TRIV effects (as well as the similar effects related to TRIV and parity conserving correlation $\vec{\sigma}_n \cdot (\vec{p} \times \vec{I}) \cdot (\vec{p} \cdot \vec{I})$) is the absence of false TRIV effects due to the final state interactions (FSI) (see, for example [1] and references therein), because these effect are related to elastic scattering at a zero angle. The general theorem about the absence of FSI for TRIV effects in elastic scattering has been proved first by R. M. Ryndin [4] (see, also [5, 6, 1]). Since this theorem is very important, we give a brief sketch of the proof for the case of the zero angle elastic scattering following [4, 1]. It is well known that the T-odd angular correlations in scattering and in a particle decay have no relation to TRIV, i.e. they have non-zero values in any process with strong, electromagnetic, and weak interactions. This is because TRI, unlike parity conservation, does not provide a constrain on amplitudes of any process, but rather relates two different processes: for example, direct and inverse channels of reactions. However, for the case when the process can be described in the first Born approximation, we can relate T-odd correlations to TRIV interactions. Indeed, the unitarity condition for the scattering matrix in terms of the reaction matrix T , which is proportional to the scattering

¹ For example, the QCD θ -term can contribute to the neutron EDM but cannot be observed in K^0 -meson decays. On the other hand, the CP-odd phase of the Cabibbo-Kobayashi-Maskawa matrix was measured in K^0 -meson decays, but its contribution to the neutron EDM is extremely small and beyond the reach of the current experimental precision.

amplitude, can be written as [7]

$$T^\dagger - T = iTT^\dagger \quad (2)$$

The first Born approximation can be used when the right side of the unitarity equation is much smaller than the left side, and results in hermitian T -matrix

$$\langle i|T|f \rangle = \langle i|T^*|f \rangle, \quad (3)$$

which with TRI condition

$$\langle f|T|i \rangle = \langle -i|T|-f \rangle^* \quad (4)$$

leads to the constrain on the T -matrix as

$$\langle f|T|i \rangle = \langle -f|T|-i \rangle^*. \quad (5)$$

This condition forbids T-odd angular correlations, as is the case with the P-odd correlations when parity is conserved. (Here the minus signs in matrix elements mean the opposite signs for particle spins and momenta in the corresponding states.) For the case of the zero angle elastic scattering, the initial and final states coincide ($i = f$), and when combined with TRI condition (4), result in Eq.(5) without the violation of unitarity (3). Therefore, in this case, FSI cannot mimic T-odd correlations, which originated from TRIV interactions. Then, an observation of a non-zero value of TRIV effects in neutron transmission directly indicates TRIV, exactly like in the case of neutron EDM [8].

Moreover, these TRIV effects are enhanced [9] by a factor of about 10^6 in neutron induced nuclear reactions (the similar enhancement was observed for PV effects related to $(\vec{\sigma}_n \cdot \vec{p})$ correlation in neutron transmission through nuclear targets). Since TRIV and PV effects have similar enhancement factors, it is convenient to consider [10, 1] the ratio λ of TRIV to PV effect at the same nuclei and at the same neutron energy as the measure of TRIV effect, because for this ratio, most nuclear structure effects cancel each other out. As a result, one can estimate $\lambda \sim g_T/g_P$, where g_T and g_P are TRIV and PV nucleon nucleon coupling constants. Theoretical predictions for λ are varying from 10^{-2} to 10^{-10} for different models of the CP violation (see, for example, [11, 10, 12, 13, 14] and references therein). Therefore, one can estimate a range of possible values of the TRIV observable and relate a particular mechanism of the CP-violation to their values. These estimates show that these effects could be measured at the new spallation neutron facilities, such as the SNS at the Oak Ridge National Laboratory or the J-SNS at J-PARC in Japan. However, existing estimates of CP-violating effects for nuclear reactions have at most order of magnitude of accuracy. In this relation, it is desirable to compare the calculation of TRIV effects for complex nuclei to the calculations of the same effects for the simplest few-body systems and to the calculations of EDMs.

Using the results of the recent calculations of PV and TRIV effects in neutron deuteron scattering [15, 16, 17], one can calculate the parameter λ for this reaction and compare it to the case of the complex nuclei. Let us consider the ratio of the TRIV difference of total cross sections in Eq.(1) given in [16]

$$\begin{aligned} P_{\bar{p}p} = \frac{\Delta\sigma_{PT}}{2\sigma_{tot}} &= \frac{(-0.185 \text{ b})}{2\sigma_{tot}} [\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} - 0.0012\bar{g}_\eta^{(0)} + 0.0034\bar{g}_\eta^{(1)} \\ &- 0.0071\bar{g}_\rho^{(0)} + 0.0035\bar{g}_\rho^{(1)} + 0.0019\bar{g}_\omega^{(0)} - 0.00063\bar{g}_\omega^{(1)}] \end{aligned} \quad (6)$$

to the corresponding PV difference [15]

$$P_p = \frac{\Delta\sigma_P}{2\sigma_{tot}} = \frac{(0.395 \text{ b})}{2\sigma_{tot}} \left[h_\pi^1 + h_\rho^0(0.021) + h_\rho^1(0.0027) + h_\omega^0(0.022) + h_\omega^1(-0.043) + h_\rho^1(-0.012) \right]. \quad (7)$$

Here, we use one meson exchange model, known as the DDH model for PV nucleon interactions, to calculate both effects; in the above expressions, \bar{g} and h are meson- nucleon TRIV and PV coupling constants, correspondingly (see for details [15, 16]). From these expressions, one can see that contributions from the pion exchange are dominant for both TRIV and PV parameters. Then, taking into account only the dominant pion meson contributions, one can estimate λ as

$$\lambda = \frac{\Delta\sigma_{PT}}{\Delta\sigma_P} \simeq (-0.47) \left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26) \frac{\bar{g}_\pi^{(1)}}{h_\pi^1} \right), \quad (8)$$

which is in a good agreement with the estimate for the complex nuclei [10].

Also, we can relate the obtained parameter λ to the existing experimental constrains obtained from EDM measurements, even though the relationships are model dependent. For example, the CP-odd coupling constant $\bar{g}_\pi^{(0)}$ could be

related to the value of the neutron EDM d_n generated via a π -loop in the chiral limit [18]. Then, using the experimental limit [19] on d_n , one can estimate $\bar{g}_\pi^{(0)}$ as less than 2.5×10^{-10} . The constant $\bar{g}_\pi^{(1)}$ can be bounded using the constraint [20] on the ^{199}Hg atomic EDM as $\bar{g}_\pi^{(1)} < 0.5 \times 10^{-11}$ [21].

The comparison of the λ parameter with the constraints on the coupling constants from the EDM experiments gives us the opportunity to estimate the “discovery potential” for neutron scattering experiments as a possible factor for improving the current limits of the EDM experiments. Then, taking the DDH “best value” of $h_\pi^1 \sim 4.6 \cdot 10^{-7}$, nuclear enhancement factors, and assuming that the parameter λ could be measured with an accuracy of 10^{-5} on the complex nuclei, one can see from Eq.(8) that the existing limits on the TRIV coupling constants could be improved by two orders of magnitude. It should be noted that to obtain Eq.(8), the assumption was made that the π -meson exchange contribution is dominant for PV effects. However, there is an indication [22] that the PV coupling constant h_π^1 is much smaller than the “best value” of the DDH. Should it be confirmed by the $\vec{n} + p \rightarrow d + \gamma$ experiment, the estimate for the sensitivity of λ to the TRIV coupling constant may be increased up to two orders of magnitude, as can be seen from Eqs.(6-8). This might increase the relative values of TRIV effects by two orders of magnitude, and as a consequence, the discovery potential of the TRIV experiments could be about 10^4 .

To conclude, the TRIV effects in neutron transmission through a nuclei target are very unique TRIV observables being free from FSI, and are of the same quality as the EDM experiments. These TRIV effects are enhanced by about 10^6 due to the nuclear enhancement factor. In addition to this enhancement, they might be structurally enhanced by about 10^2 if PV π -nucleon coupling constant is less than the “best value” DDH estimate. Therefore, these types of experiments have a discovery potential of about $10^2 - 10^4$ for the improvement of the current limits on the TRIV interaction obtained from the EDM experiments.

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